

THE RADIAL VELOCITY TATOOINE SEARCH FOR CIRCUMBINARY PLANETS

Maciej Konacki

Nicolaus Copernicus Astronomical Center
Polish Academy of Sciences

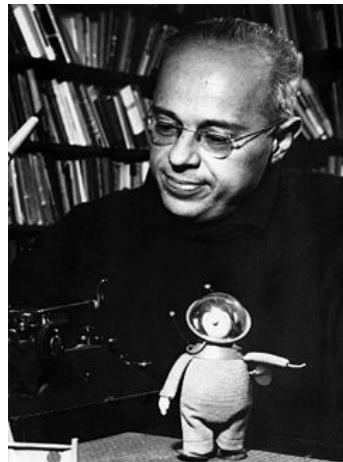
CIRCUMBINARY PLANETS IN POP CULTURE – TATOOINE AND SOLARIS



“Star Wars” (1977)



SOLARIS BY STANISLAW LEM

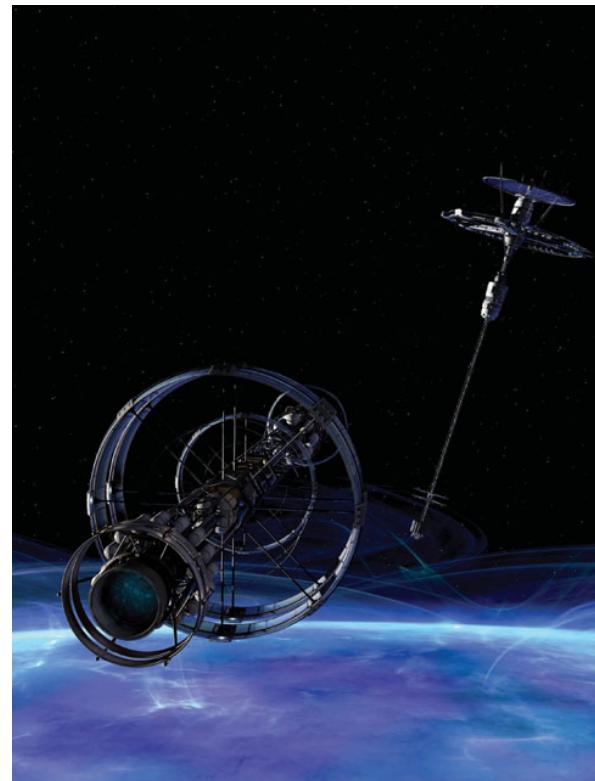


“The planet orbits two suns: a red sun and a blue sun.
(...) Solaris’ orbit was unstable. (...) “

S. Lem, “Solaris” (1961)

1921-2006

Soderbergh's movie (2002)



NUMERICAL EXPERIMENTS ON PLANETARY ORBITS IN DOUBLE STARS, DVORAK, 1984

Three types of planetary orbits in binary star systems:

Planet type orbits (P-type) – circumbinary planets

Sattelite type orbits (S-type) – circumprimary and circumsecondary planets

Librator type orbits (L-type) – planets orbiting Lagrange points L4 and L5

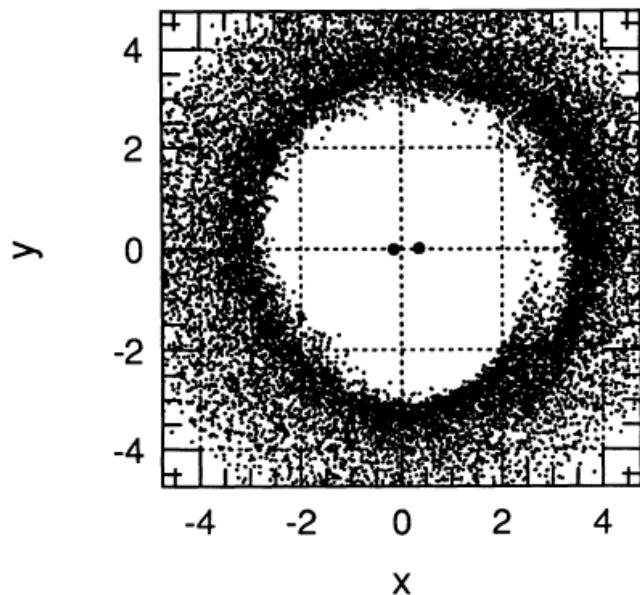
*Planetary orbits in binary star systems
may be dynamically stable*



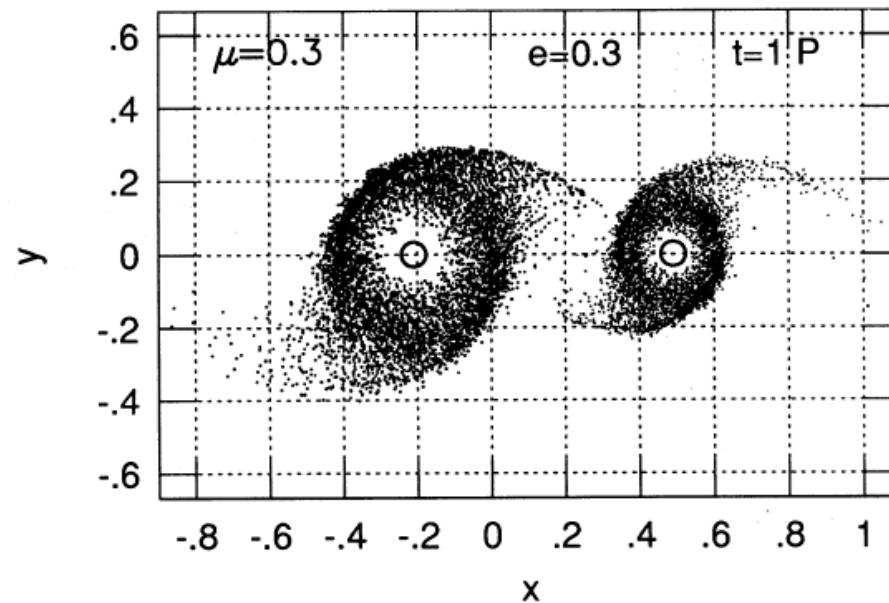
DYNAMICS OF BINARY-DISK INTERACTION

ARTYMOWICZ & LUBOW, 1994

Circumbinary disk



Circumprimary/secondary disk

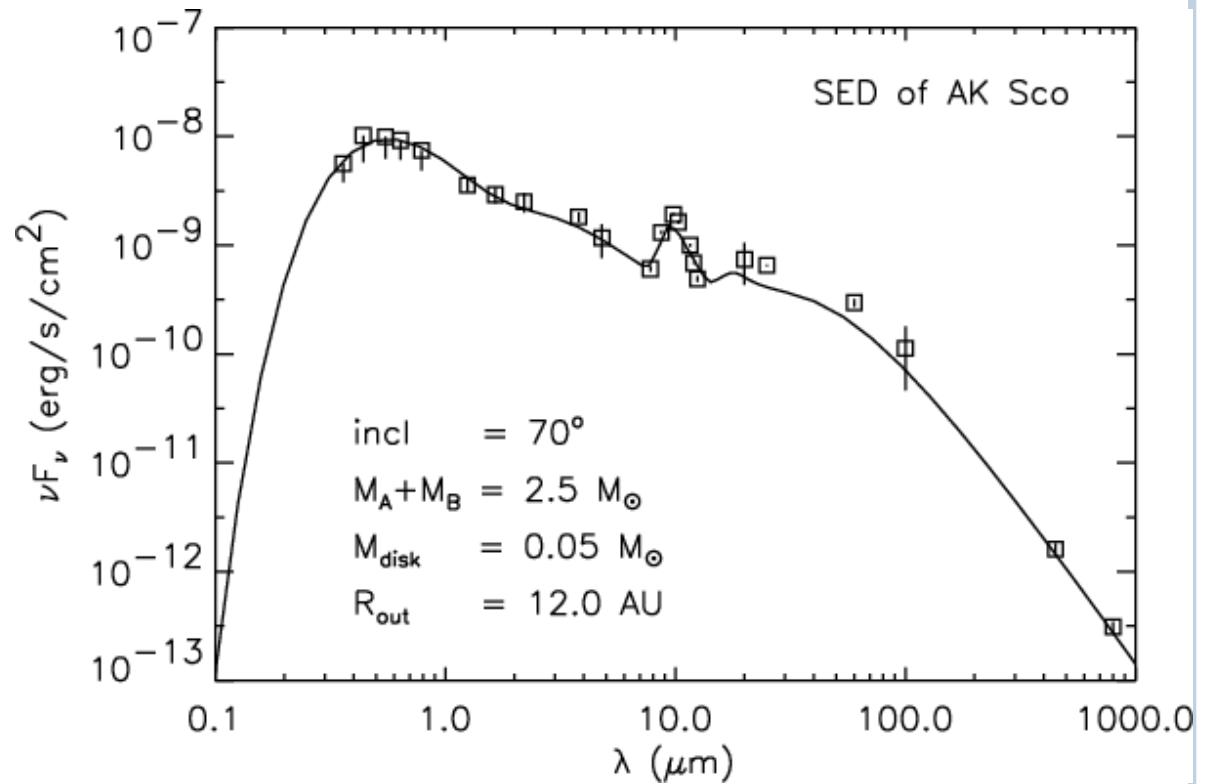


Inner edge: 1.8-2.6 a
(depending on eccentricity)



YOUNG SPECTROSCOPIC BINARIES WITH CIRCUMBINARY DISKS – AN EXAMPLE, AK SCO

AK Sco, P=13.6 d, e=0.47
F5+F5, age \sim 10 Myrs
 $R_{\text{in}} = 0.4 \text{ AU}$
(Alencar et al 2003)



CENSUS OF CIRCUMBINARY PLANETS OR PLANETARY CANDIDATES

PSR B1620-26

(1993, 2003, 1 planet around a binary pulsar, *pulsar timing*)

HD202206

(2002, 1 planet around a star and a brown dwarf, *radial velocity*)

HW Vir

(2009, 1 planet + 1 brown dwarf around a binary star, *eclipse timing*)

NN Ser

(2009, 1 planet around a binary star, *eclipse timing*)

DP Leo

(2009, 1 planet around a binary star, *eclipse timing*)

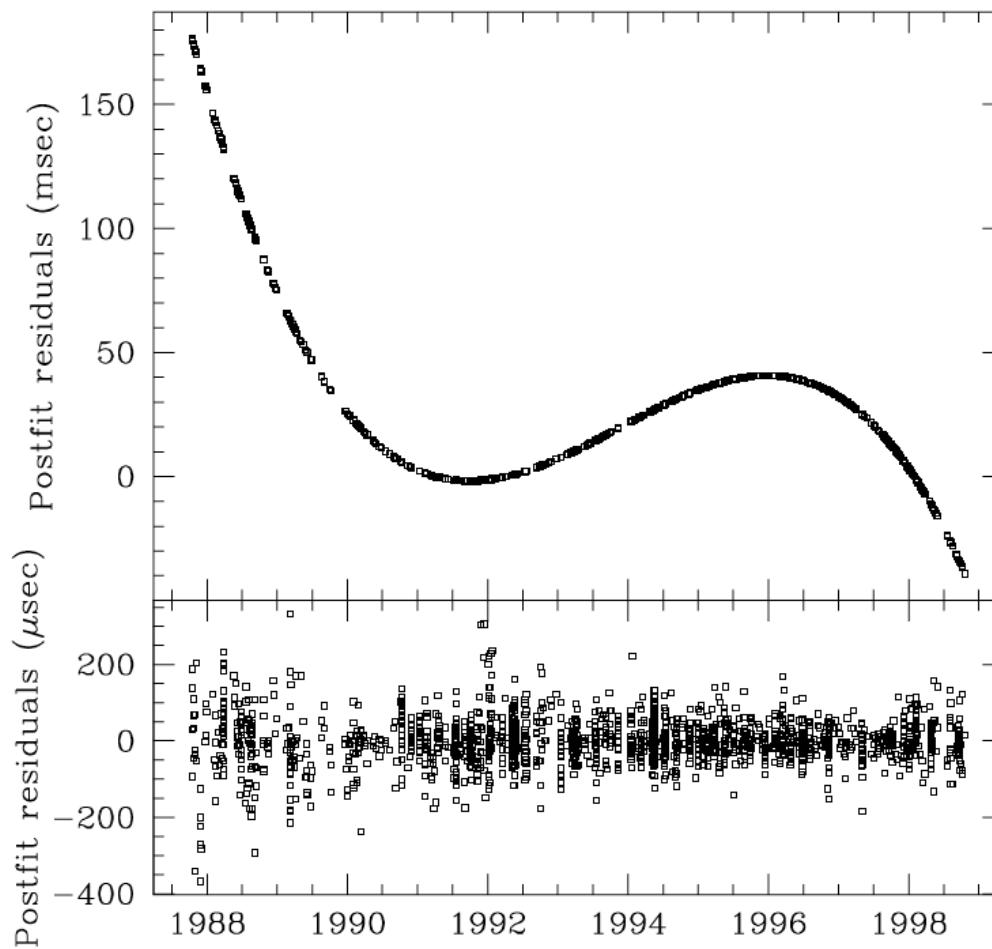
QS Vir

(2010, 1 planet around a binary star, *eclipse timing*)



PSR B1620-26

Spin period P (ms)	11.0757509142025 (18)
Spin frequency f (Hz)	90.287332005426 (14)
\dot{f} (s^{-2})	$-5.4693 (3) \times 10^{-15}$
\ddot{f} (s^{-3})	$1.9283 (14) \times 10^{-23}$
$f^{(3)}$ (s^{-4})	$6.39 (25) \times 10^{-33}$
$f^{(4)}$ (s^{-5})	$-2.1 (2) \times 10^{-40}$
$f^{(5)}$ (s^{-6})	$3 (3) \times 10^{-49}$



Thorsett et at, 1999

PSR B1620-26

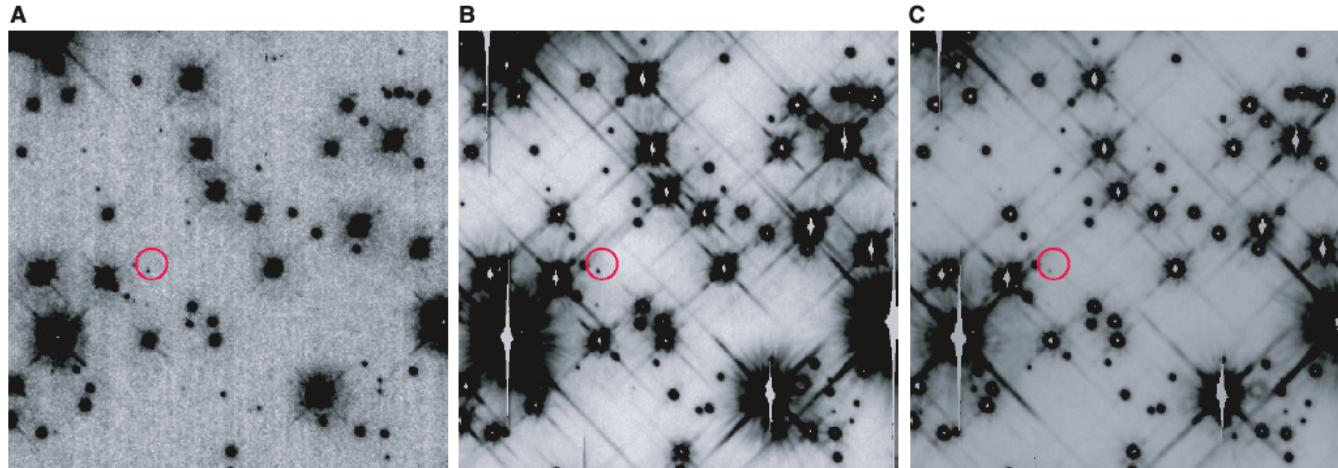


Fig. 1. (A to C) Hubble Space Telescope images of the field where the pulsar is located. The position of the pulsar is indicated by the center of the circle, which has a radius of 0.7''. The three images are the U (F336W), V (F555W), and I (F814W) bandpasses, which are wide-band filters centered on 336 nm, 555 nm, and 814 nm, respectively.

White dwarf: $0.34 +/ - 0.04 M_{\text{Sun}}$

Orbital inclination PSR-WD: ~ 55 deg
(assuming $M_{\text{PSR}} = 1.35 M_{\text{sun}}$)

Planet: $a \sim 23$ AU, mass $\sim 2.5 +/ - 1 M_{\text{Jup}}$

Sigurdsson et al, 2003

HD202206

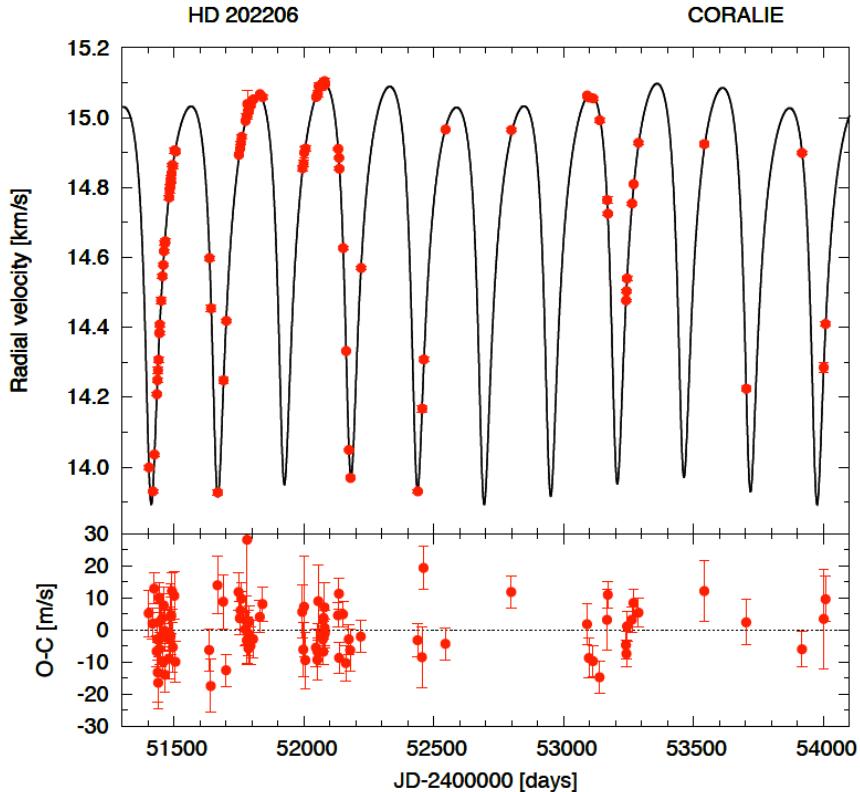
Table 1. Best Newtonian fit **S1** for the HD202206 system assuming $i_b = i_c = 90^\circ$, and $\Delta\Omega = 0^\circ$.

Param.	S1	inner	outer
V_0	[km/s]		14.729 ± 0.001
P	[days]	256.389 ± 0.044	1397.445 ± 19.056
K	[m/s]	564.82 ± 1.42	38.08 ± 1.21
e		0.431 ± 0.001	0.104 ± 0.024
ω	[deg]	161.91 ± 0.27	105.56 ± 15.77
$M + \omega$	[deg]	239.016 ± 0.13	250.38 ± 2.71
a	[AU]	0.8053	2.4832
i	[deg]	90	90
Ω	[deg]	0	0
m	[M_{Jup}]	16.59	2.179
Date	[JD-2400000]		53000.00
rms	[m/s]		7.4544
$\sqrt{\chi^2_r}$			1.411

Errors are given by the standard deviation σ . This fit corresponds to a coplanar system seen edge-on, with minimum values for the masses.

Table 2. Stable orbital parameters **S2** for the HD202206 system for $i_b = i_c = 90^\circ$ and $\Delta\Omega = 0^\circ$. Using the fit **S1** as a starting point (Table 1), we select a value for the semi-major axis of the outer planet such that the system becomes stabilized in the 5:1 mean motion resonance. This orbit is marked by a white filled circle in Fig. 6.

Param.	S2	inner	outer
a	[AU]	0.8053	2.49
i	[deg]	90	90
e		0.431	0.104
$M + \omega$	[deg]	239.016	250.38
ω	[deg]	161.91	105.56
Ω	[deg]	0	0
m	[M_{Jup}]	16.59	2.179
Date	[JD-2400000]		53000.00
$\sqrt{\chi^2_r}$			1.4136



5:1 MMR likely

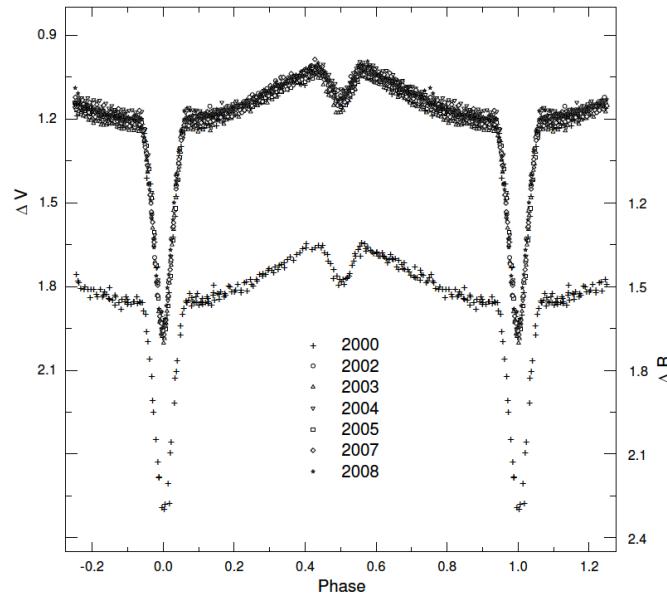
Coplanar stable configurations:

$$M_1 \sim 16.6\text{-}33.5 M_{Jup}$$

$$M_2 \sim 2.2\text{-}4.4 M_{Jup}$$

Couetdic et al, 2009

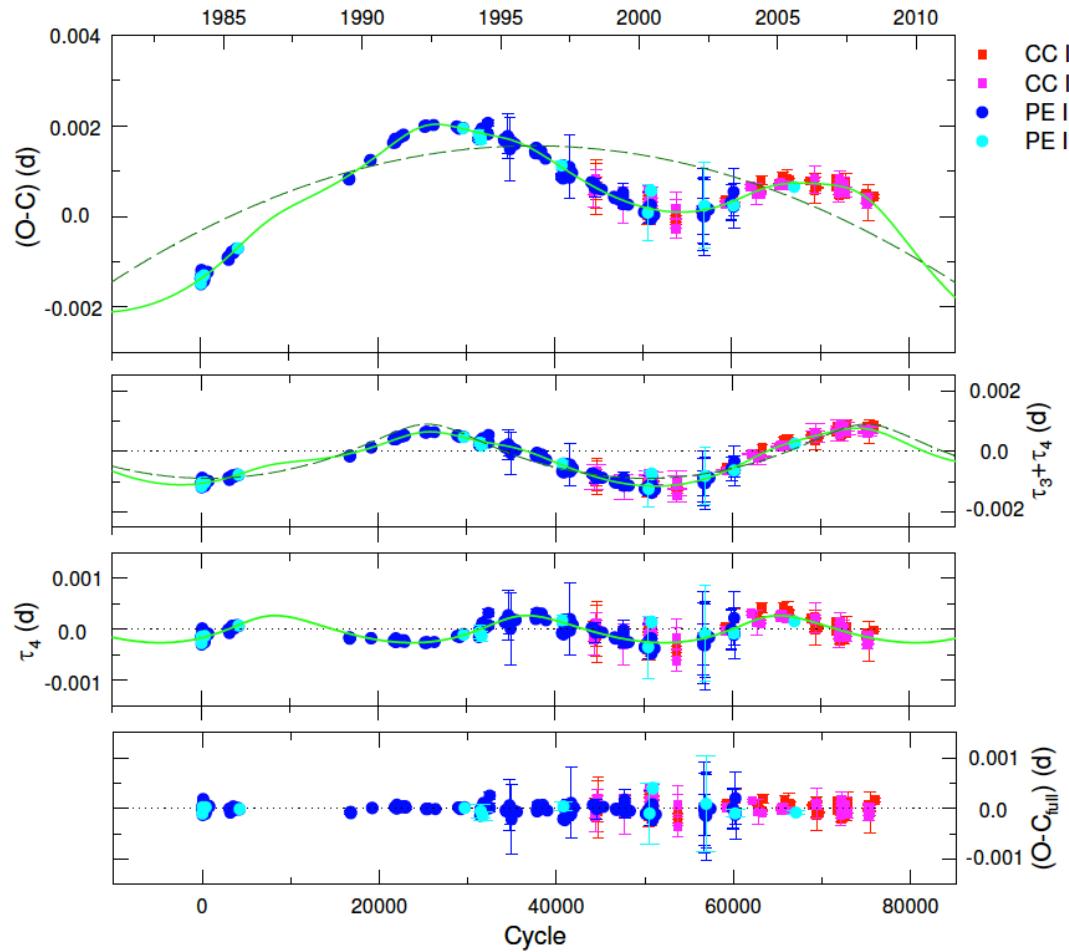
HW VIR



sdB+M6 eclipsing binary
 $P = 2.8 \text{ hr}$
 $0.48 + 0.14 M_{\text{sun}}$
 $a = 0.86 R_{\text{sun}}$

Angular momentum loss via magnetic
breaking of the cool secondary

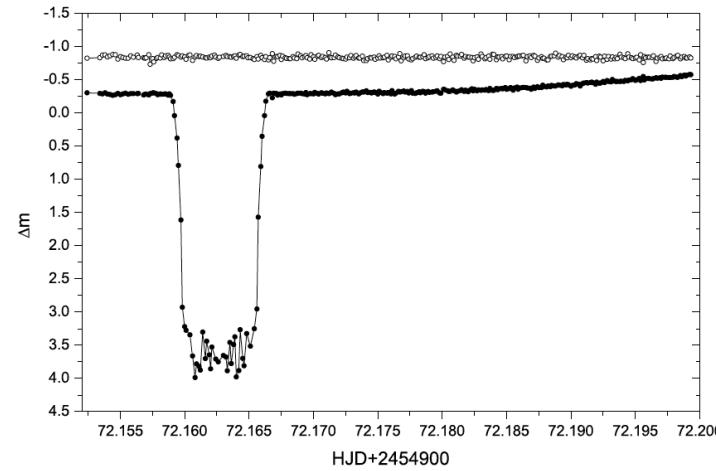
Lee et al, 2009



C1: $P = 15.8 \text{ yr}$, $M \sin(i) = 19.2 M_{\text{Jup}}$,
 $e = 0.5$, $A = 77 \text{ sec}$
C2: $P = 9.1 \text{ yr}$, $M \sin(i) = 8.4 M_{\text{Jup}}$,
 $e = 0.3$, $A = 23 \text{ sec}$



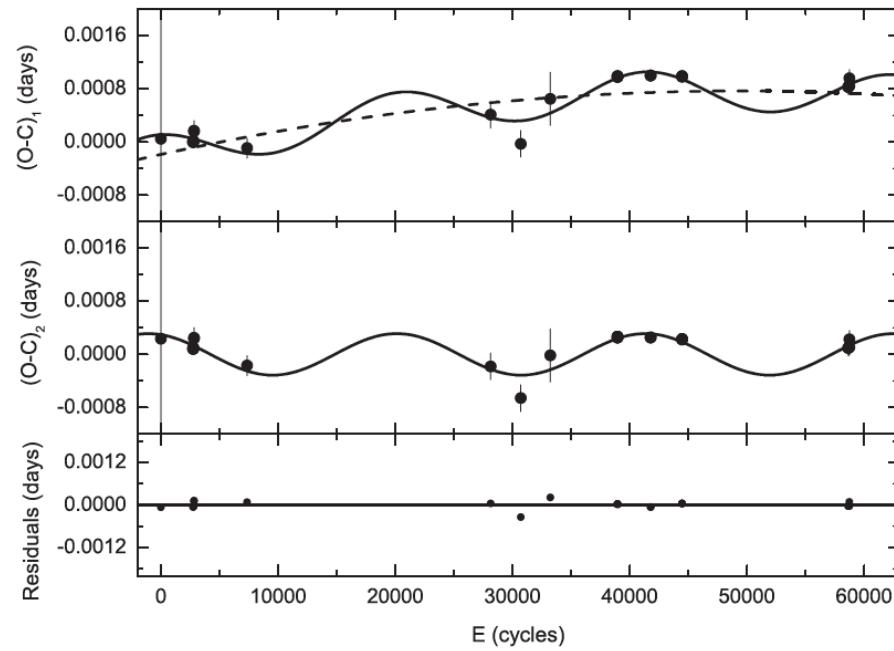
NN SER



White dwarf-red dwarf
eclipsing binary
 $M_1 + M_2 = 0.65 M_{\text{Sun}}$
 $P = 3.12 \text{ hr}$

Angular momentum loss

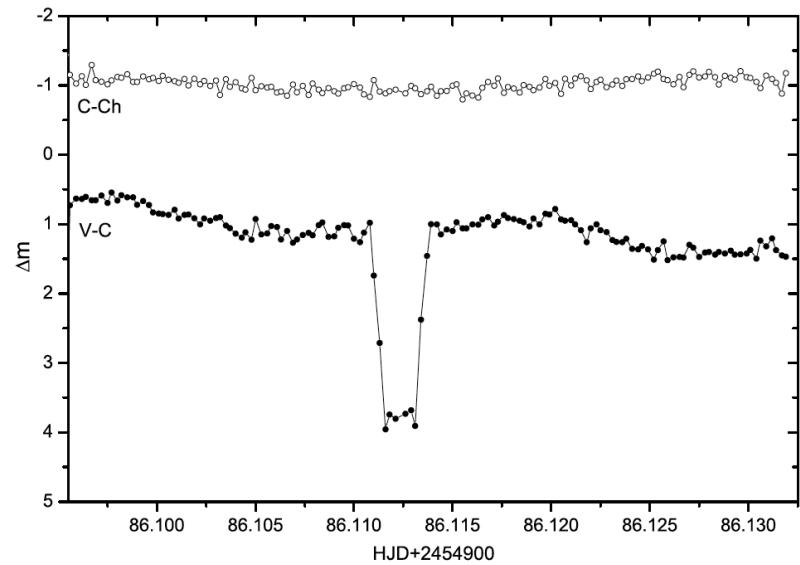
Qian et al, 2009



Tertiary: $P = 7.6 \text{ yr}$,
 $M \sin(i) = 11.1 M_{\text{Jup}}$,
 $A = 27 \text{ sec}$

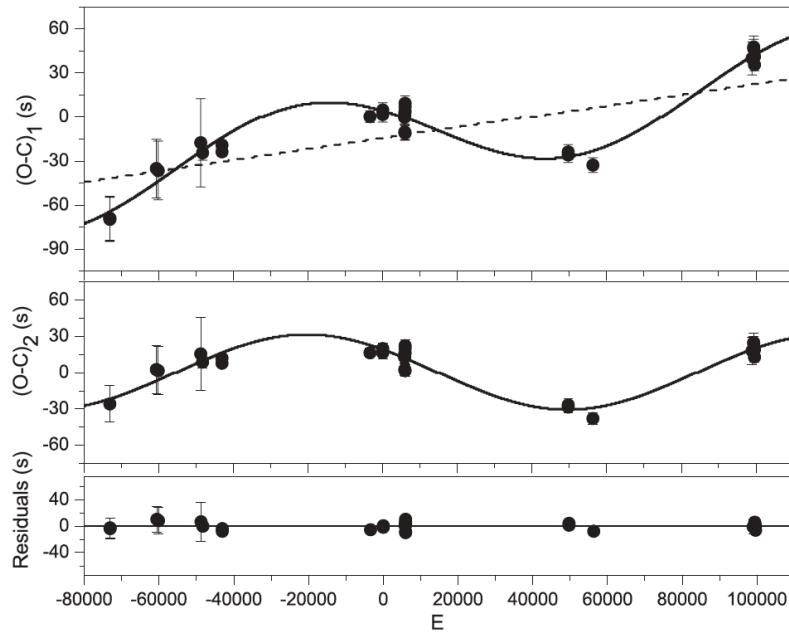


DP LEO



Eclipsing AM Her-type binary (polar – cataclysmic variable, strongly magnetic)
 $M_1 + M_2 = 0.69 M_{\text{Sun}}$
 $P = 1.5 \text{ hr}$

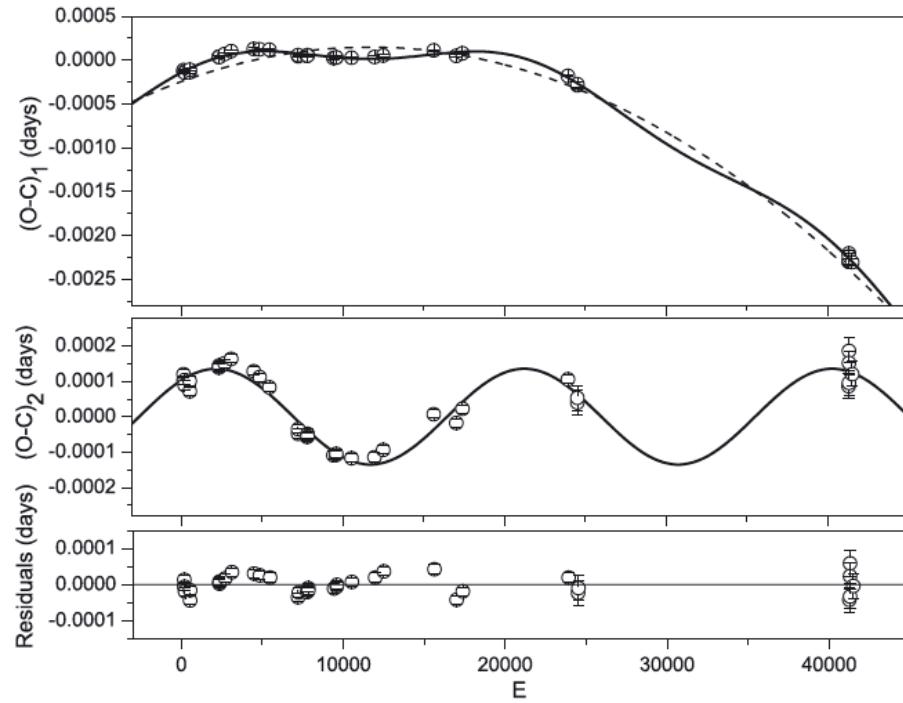
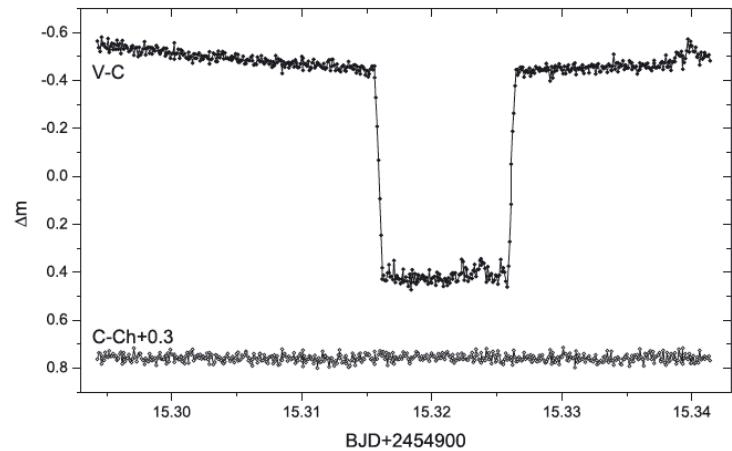
Qian et al, 2010



Tertiary: $P = 23.8 \text{ yr}$,
 $M \sin(i) = 6.3 M_{\text{Jup}}$,
 $A = 31.5 \text{ sec}$



QS VIR



White dwarf-red dwarf eclipsing binary
 $M_1 + M_2 = 1.2 M_{\text{Sun}}$
 $P = 3.6 \text{ hr}$

Angular momentum loss

Tertiary: $P = 7.9 \text{ yr}$,
 $M \sin(i) = 6.6 M_{\text{Jup}}$,
 $e=0.4$
 $A = 12 \text{ sec}$

Qian et al, 2010

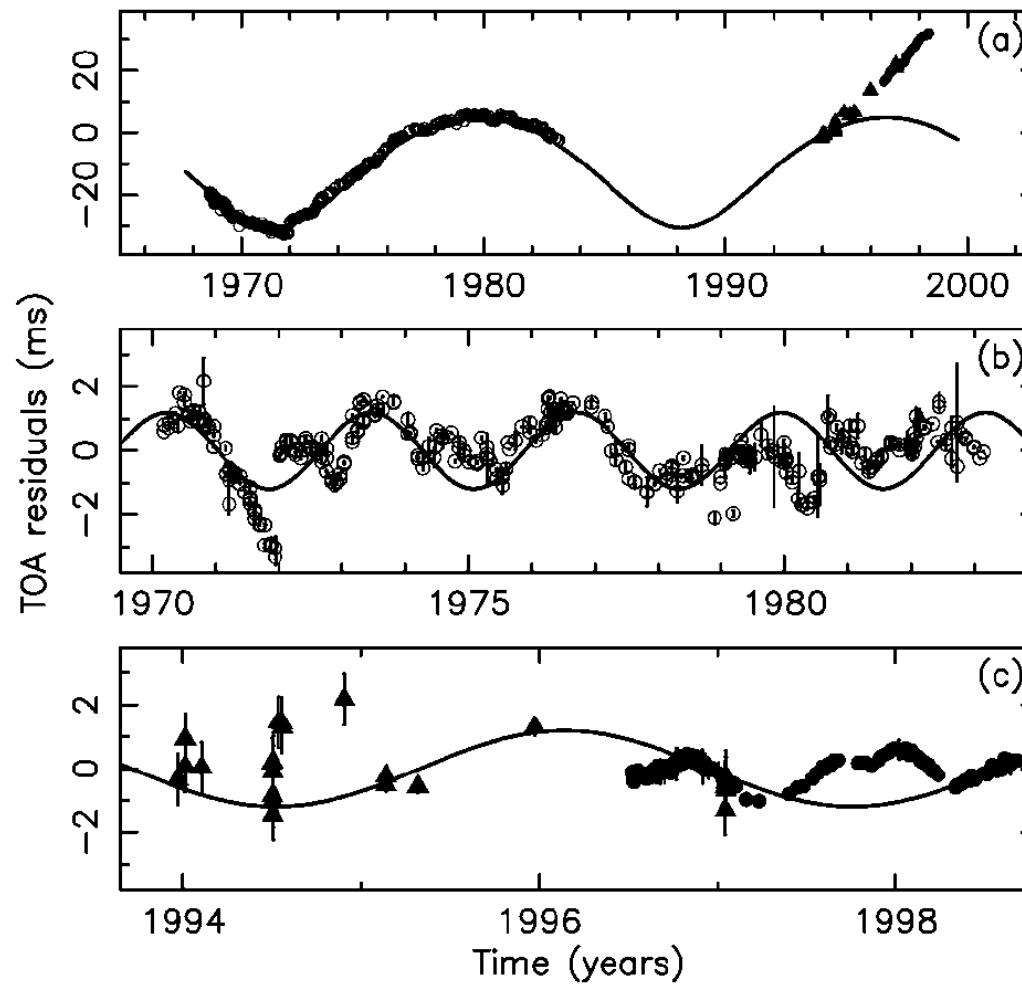
PSR B0329+54 AND ITS TIMING NOISE

Two “planets”:

3 yr orbital period
(Demiański &
Proszynski, 1979)

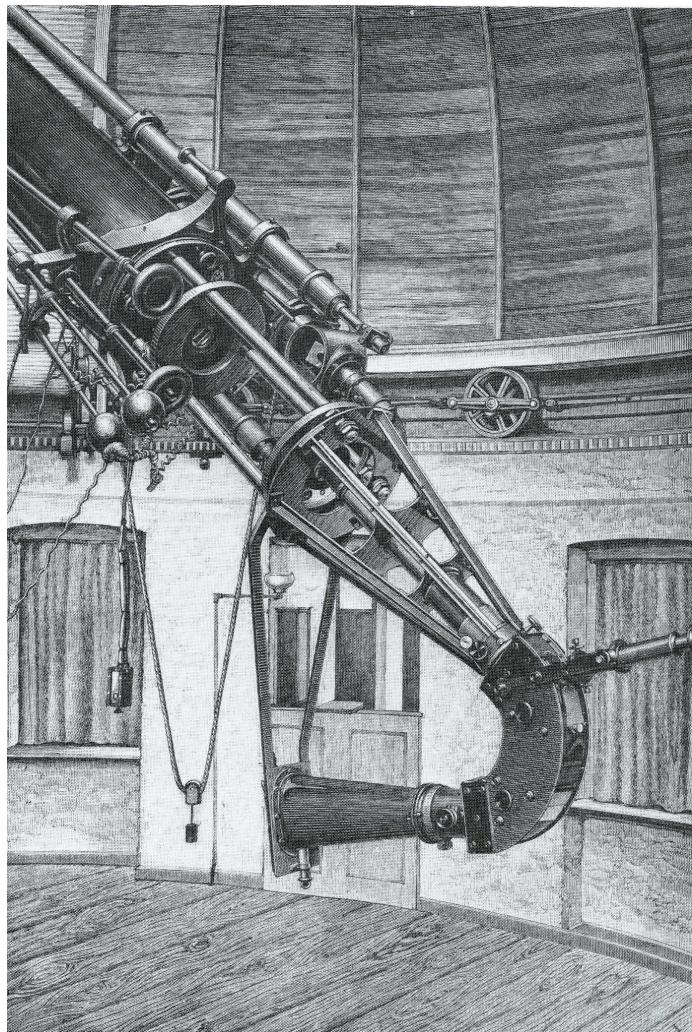
and

17 yr orbital period
(Shabanova, 1995)



Konacki, Lewandowski, Wolszczan et al, 1999 – no planets

BEGINNINGS OF STELLAR SPECTROSCOPY - LATE XIXTH CENTURY

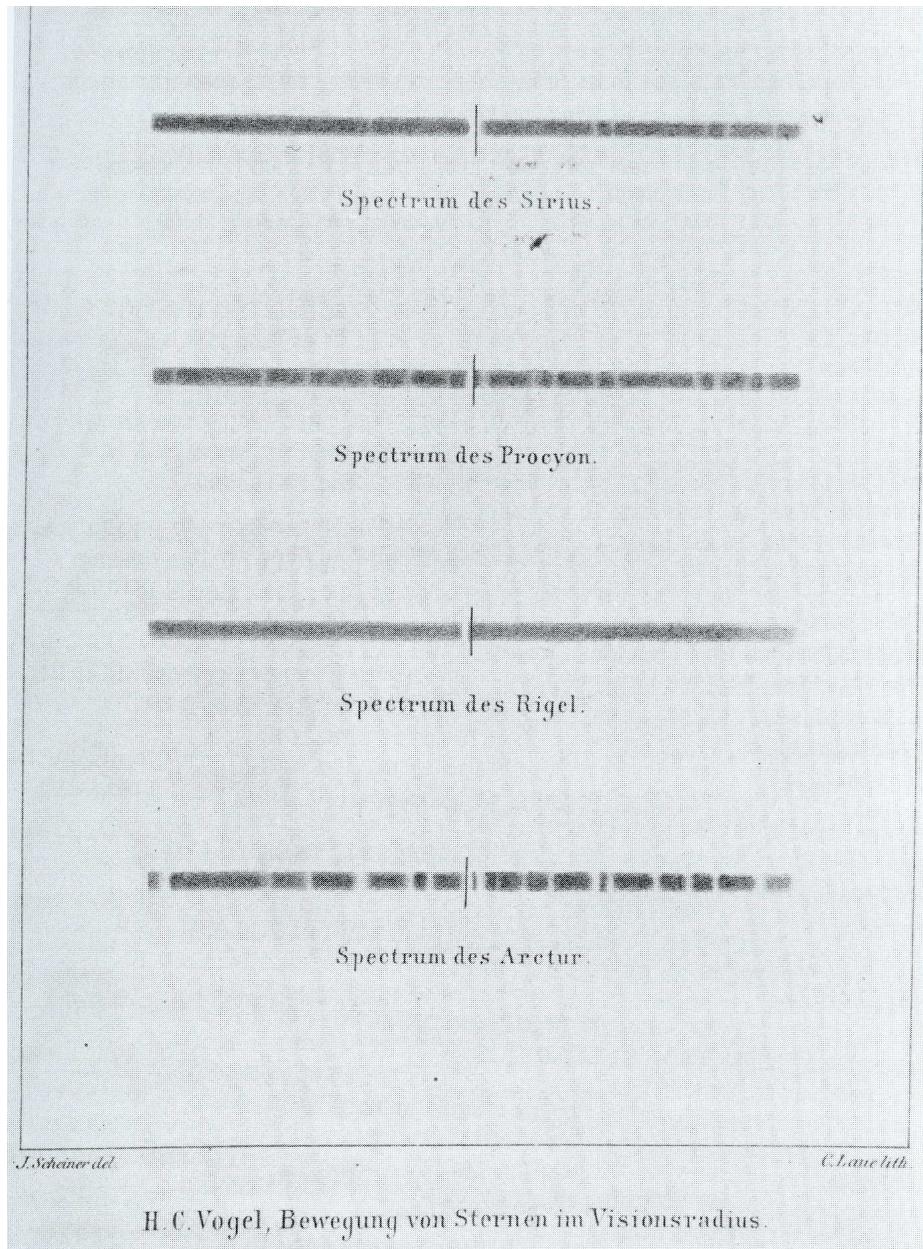


Hermann C. Vogel's prism
spectrograph on the 30-cm
refractor at Potsdam Observatory
1889

Vogel perfected the measurement
of radial velocities of stars using
photographic plates

RV precision of several km/s





Vogel, 1892

H-gamma and the emission
line from a discharge tube

For more see
[http://cosmicdiary.org/
blogs/john_hearnshaw/?
p=384](http://cosmicdiary.org/blogs/john_hearnshaw/?p=384) by J. Hearnshaw

Vogel, 28 Nov 1889, Algol – SB1

1890AN....123...2

ASTRONOMISCHE NACHRICHTEN.

Nº 2947.

Spectrographische Beobachtungen an Algol.

Von Prof. H. C. Vogel.

Nachdem durch eine grosse Reihe hier ausgeführter Beobachtungen die Ueberlegenheit der spectrographischen Methode zur Ermittelung der Bewegung von Sternen im Visionsradius, über welche ich kurz in Nr. 2896 der A. N. fallend grosse Bewegung haben könne. Auch die später in Greenwich gemachten Beobachtungen haben bisher kein Ergebniss geliefert, aus welchem eine Bewegung Algols abgeleitet werden könnte.

Pickering, 13 Nov 1889, Mizar – SB2

80

Spectrum of ξ Ursæ Majoris. [No. 159.

*On the Spectrum of ξ Ursæ Majoris *.*

In the Third Annual Report of the Henry Draper Memorial attention is called to the fact that the K line in the spectrum of ξ Ursæ Majoris occasionally appears double. The spectrum of this star has been photographed at the Harvard College Observatory on seventy nights, and a careful study of the results has been made by Miss A. C. Maury, a niece of Dr. Draper. The K line is clearly seen to be double in the photographs taken on March 29, 1887, on May 17, 1889, and on August 27 and 28, 1889. On many other dates the line appeared hazy, as if the components were slightly separated, while at other times the line appears to be well defined and single. An examination of all the

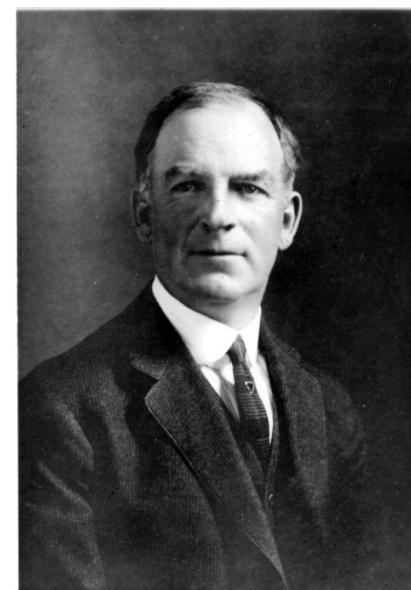
PICKERING, VOGEL AND CAMPBELL



1846-1919
Director of Harvard
College Obs. for 42
years
Bruce Medalist, 1908



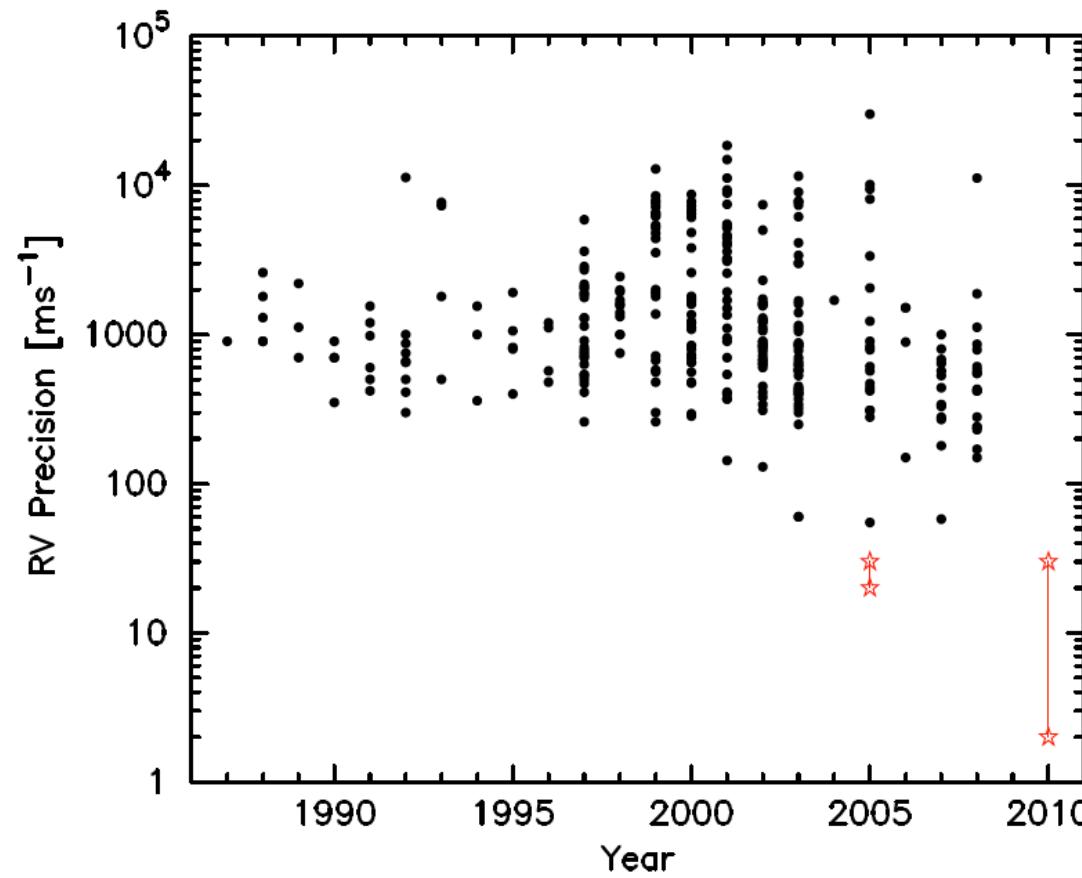
1841-1907
Director of Potsdam
Obs. for 25 years
Bruce Medalist, 1906



1862-1938
Director of Lick Obs.
for 30 years
Bruce Medalist, 1915

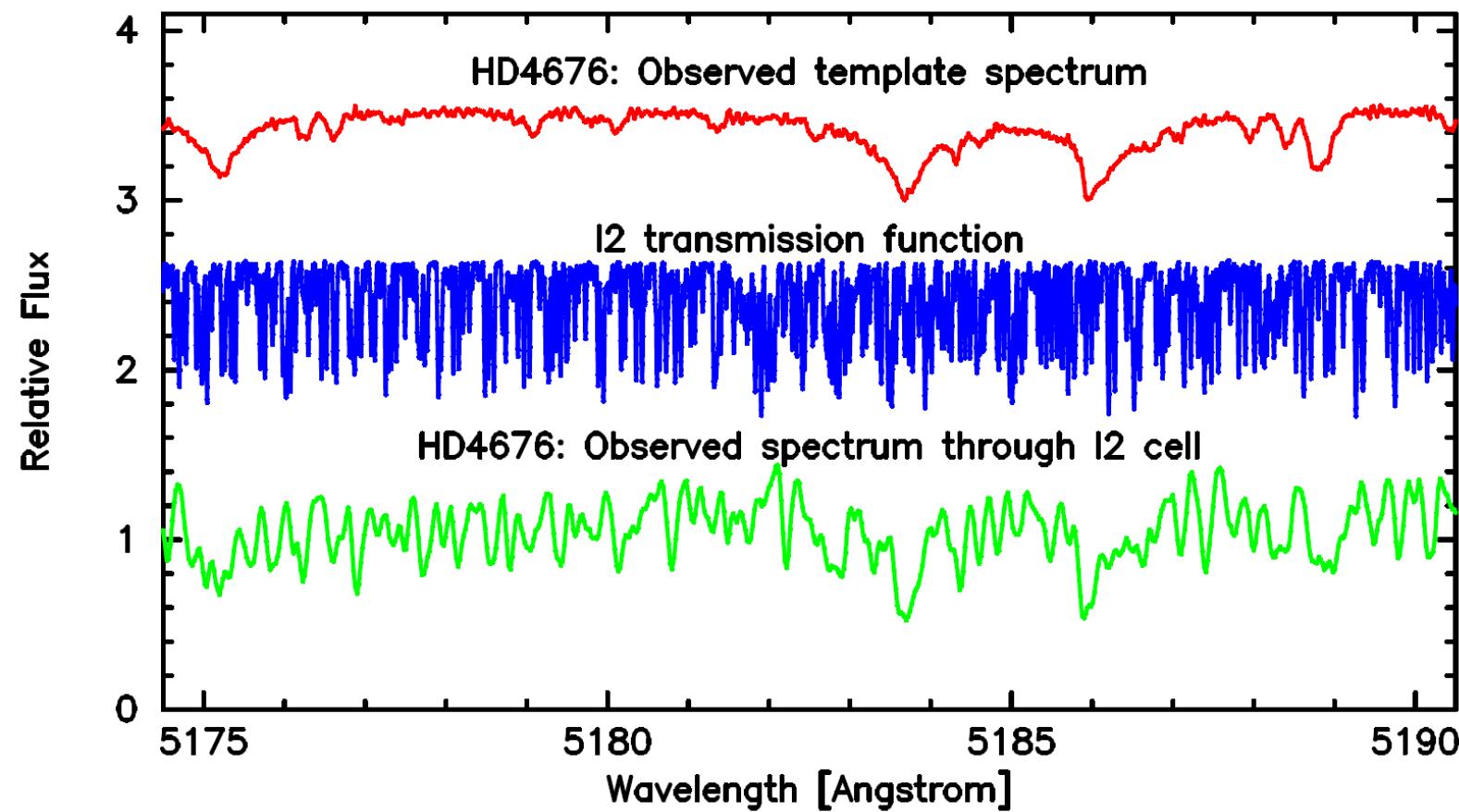
Importance of flexure and temperature control (Vogel 1890, Campbell 1898)
Impact of slit illumination on RV precision (Campbell 1916)
First catalog of spectroscopic binaries (Campbell 1911)

RADIAL VELOCITY PRECISION OF DOUBLE-LINED BINARY STARS

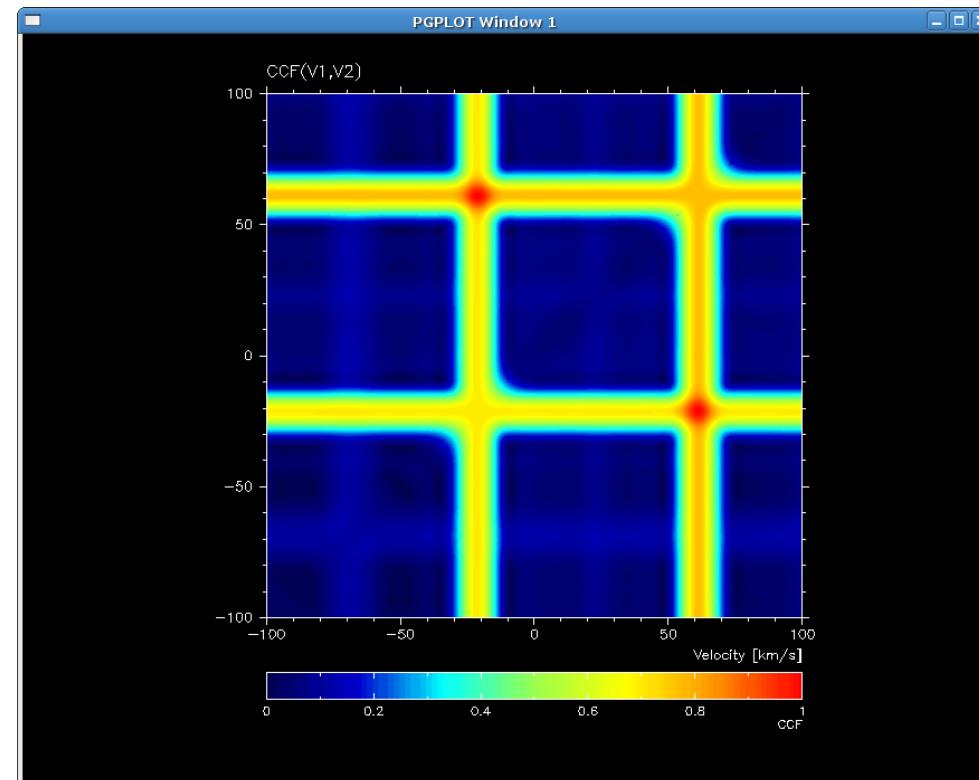
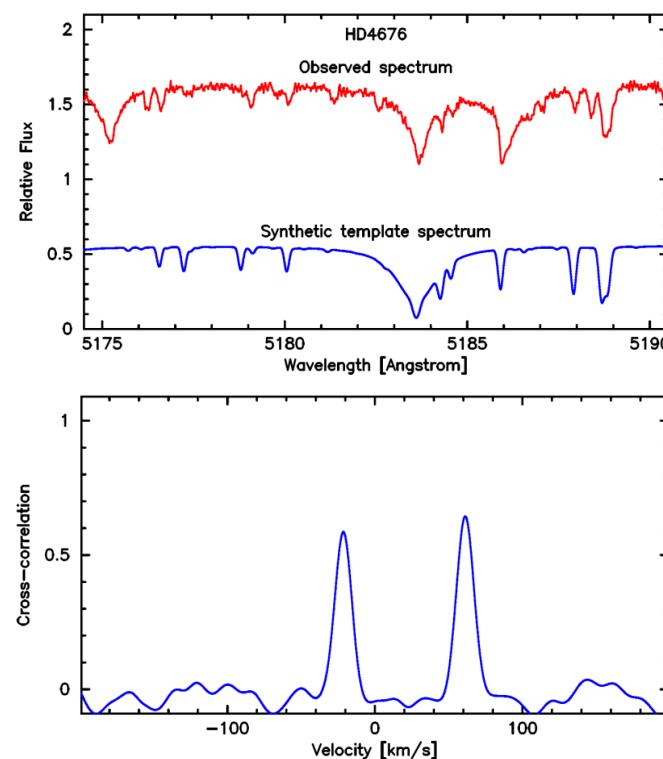


Konacki et al 2010, submitted to ApJ, arXiv:0910.4482

IODINE CELL AND PRECISION RVs

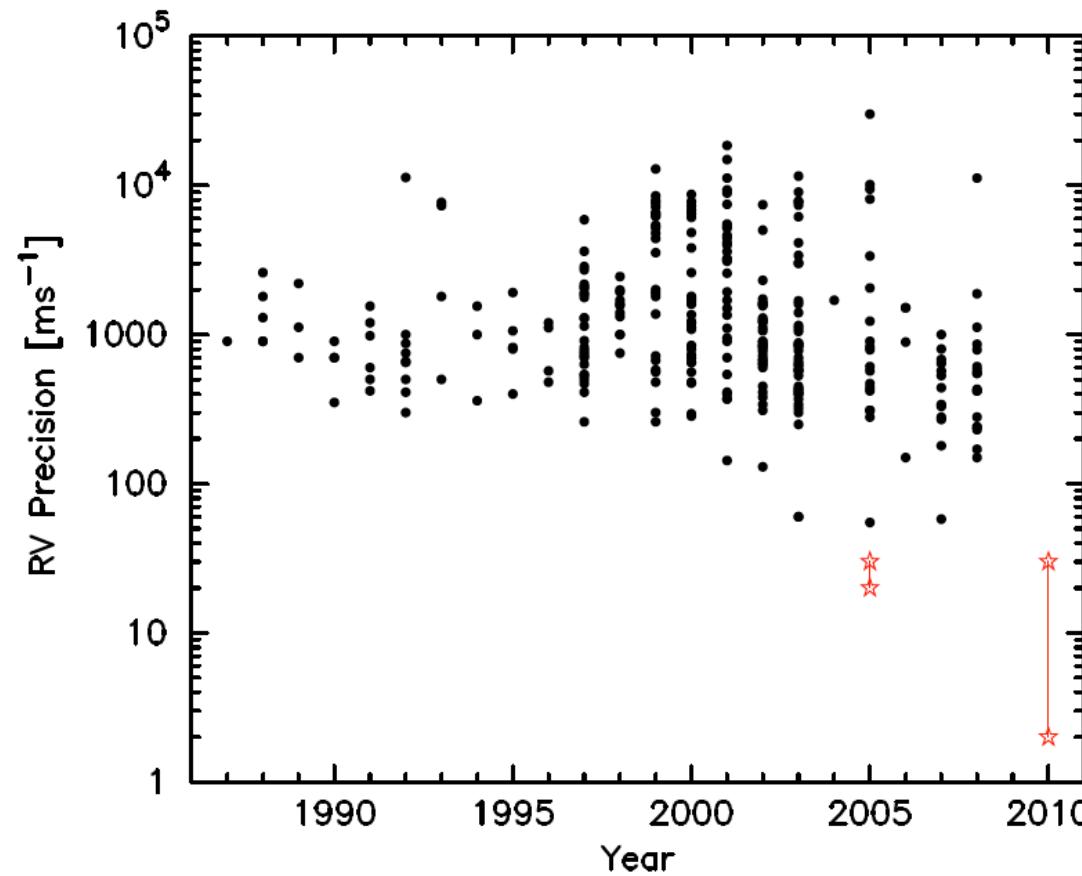


RVS OF DOUBLE-LINED BINARY STARS – WITH TODCOR – 20-30 M/S



TODCOR – two dimensional cross-correlation (Zucker & Mazeh, 1994)

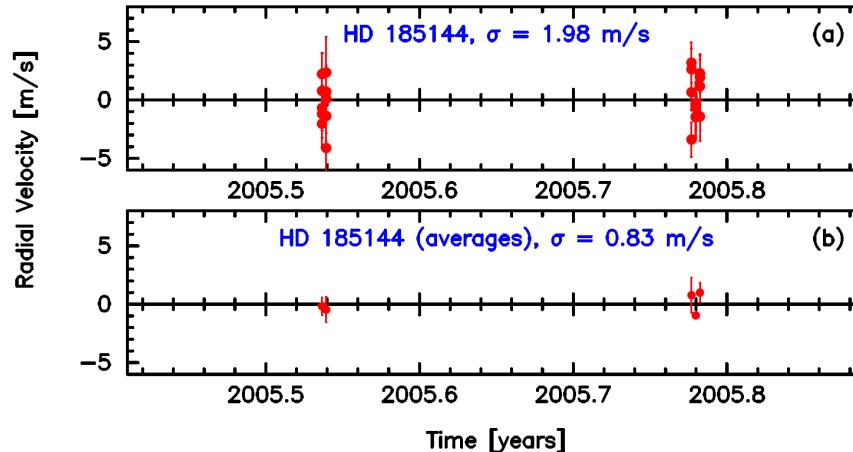
RADIAL VELOCITY PRECISION OF DOUBLE-LINED BINARY STARS



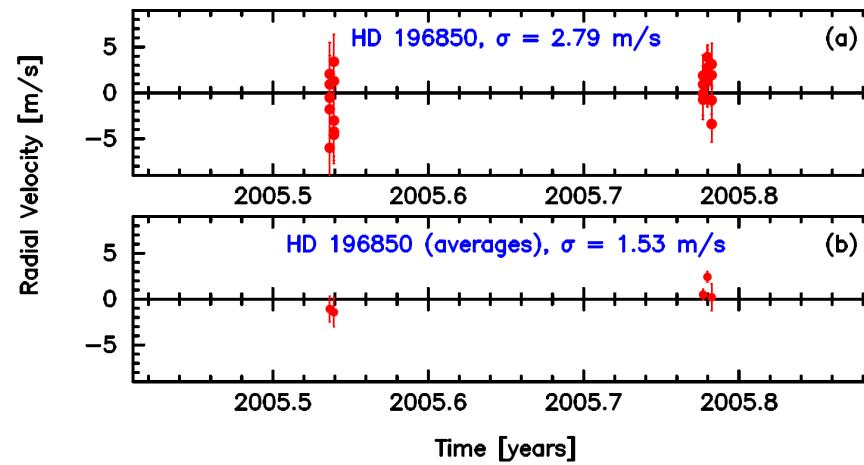
Konacki et al 2010, submitted to ApJ, arXiv:0910.4482

NEW I2 DATA PIPELINE

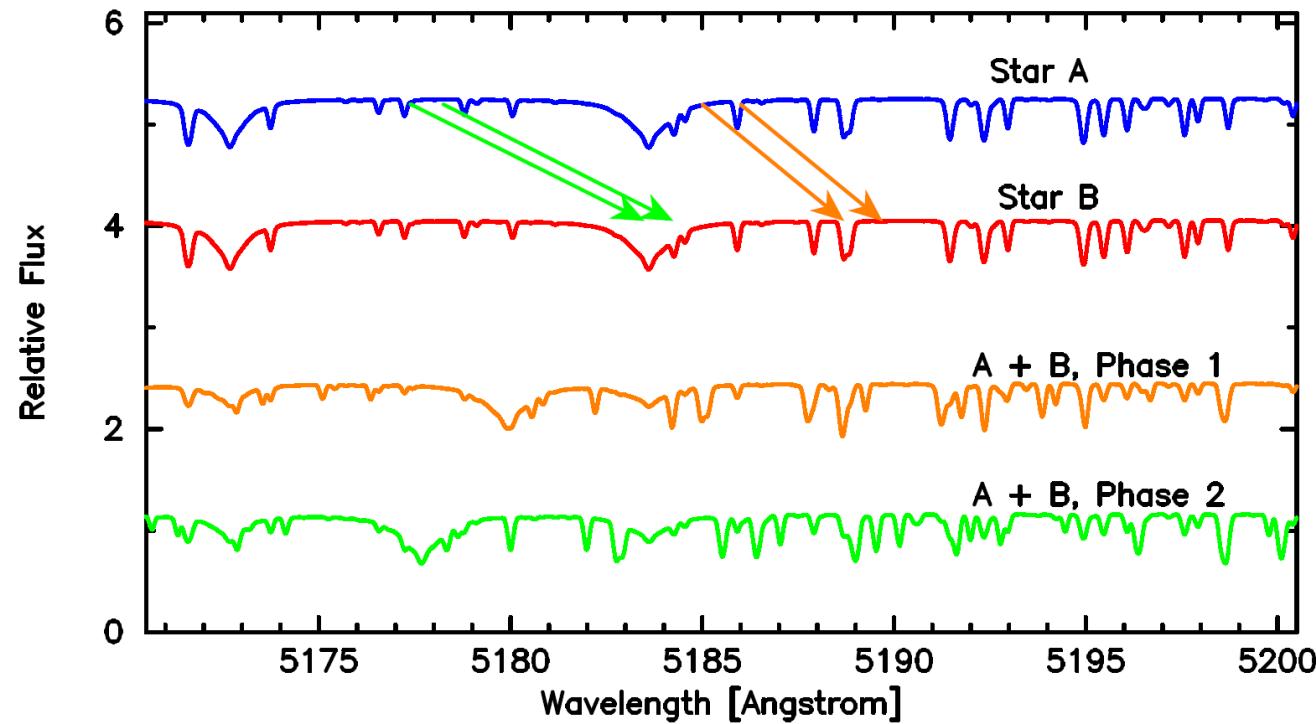
HD185144, V=4.7, K0V
SNR ~600 per pixel
Time span: 3 months



HD196850, V=6.8, G0V
SNR ~600 per pixel
Time span: 3 months



TOMOGRAPHIC DISENTANGLING



Idea: Bagnuolo & Gies 1991

Numerical realization: Konacki et al 2010, ApJ, submitted, astroph/0910.4482

The method will also work on spectra from non-iodine spectrographs such as HARPS



TATOOINE SEARCH FOR CIRCUMBINARY PLANETS

The Attempt To Observe Outer-planets In Non-single-stellar Environments

Team: M. Konacki, M. Muterspaugh, S. Kulkarni, A. Howard, S. Brown, K. Helminiak

Northern Hemisphere:

2003-2007 Keck/HIRES (since 2005 in collaboration with S. Kulkarni)

2006-2007 TNG/SARG (Canary Islands)

2006- 3-m/0.9-m/Hamspec (Lick Observatory)
in collaboration with Matt Muterspaugh (TSU),
A. Howard, S. Brown (UCB)

Total sample: ~50 SB2s (mostly non eclipsing, for now) and increasing

Time span varies ~1-6 years

Southern Hemisphere:

SALT/HRS (South Africa, Polish share 10%) ~2011?



HD78418

HD78418

G5IV-V

V = 5.9 mag

P = 19.4 days

e = 0.20

K₁ = 26.8 km/s

K₂ = 30.7 km/s

Keck I/HIRES:

SNR ~250 per pixel

r = 2.3

SNR primary ~175

SNR secondary ~75

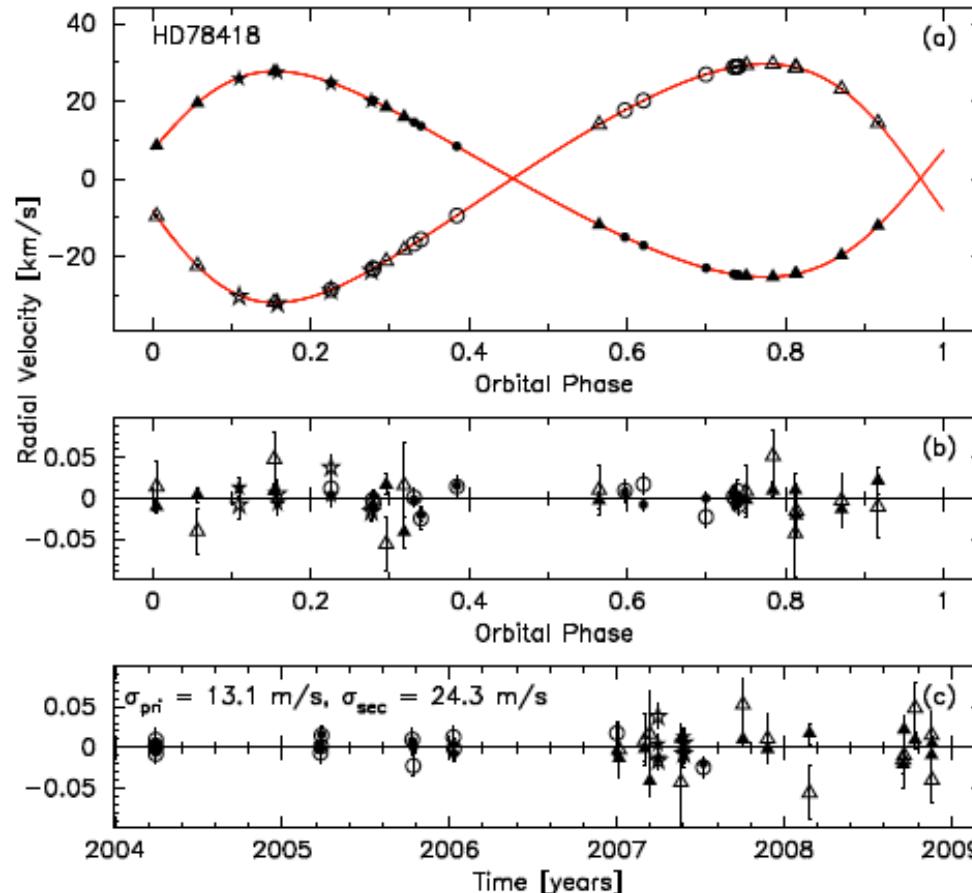
RMS primary 6.9 m/s

RMS secondary 14.3 m/s

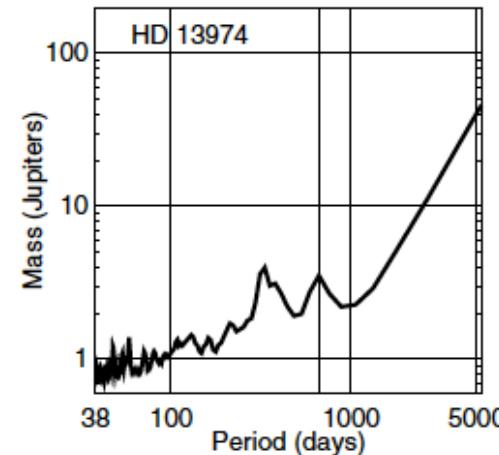
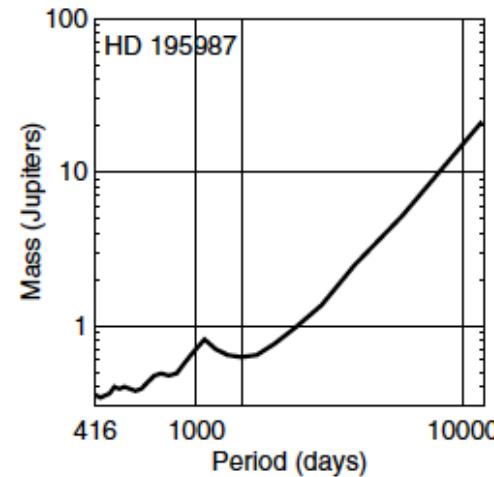
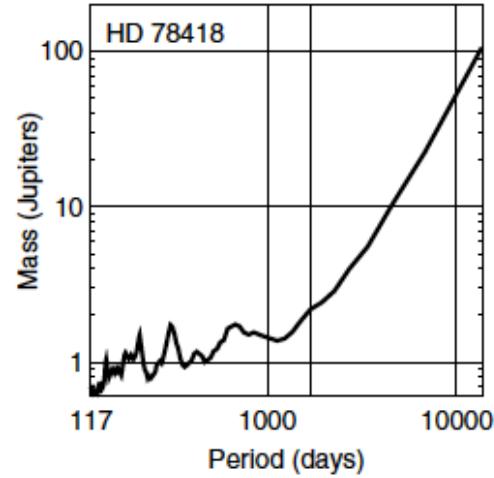
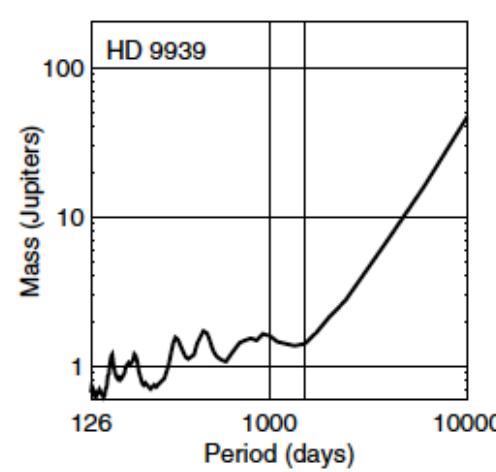
Total:

58 measurements

Time span: 5 years

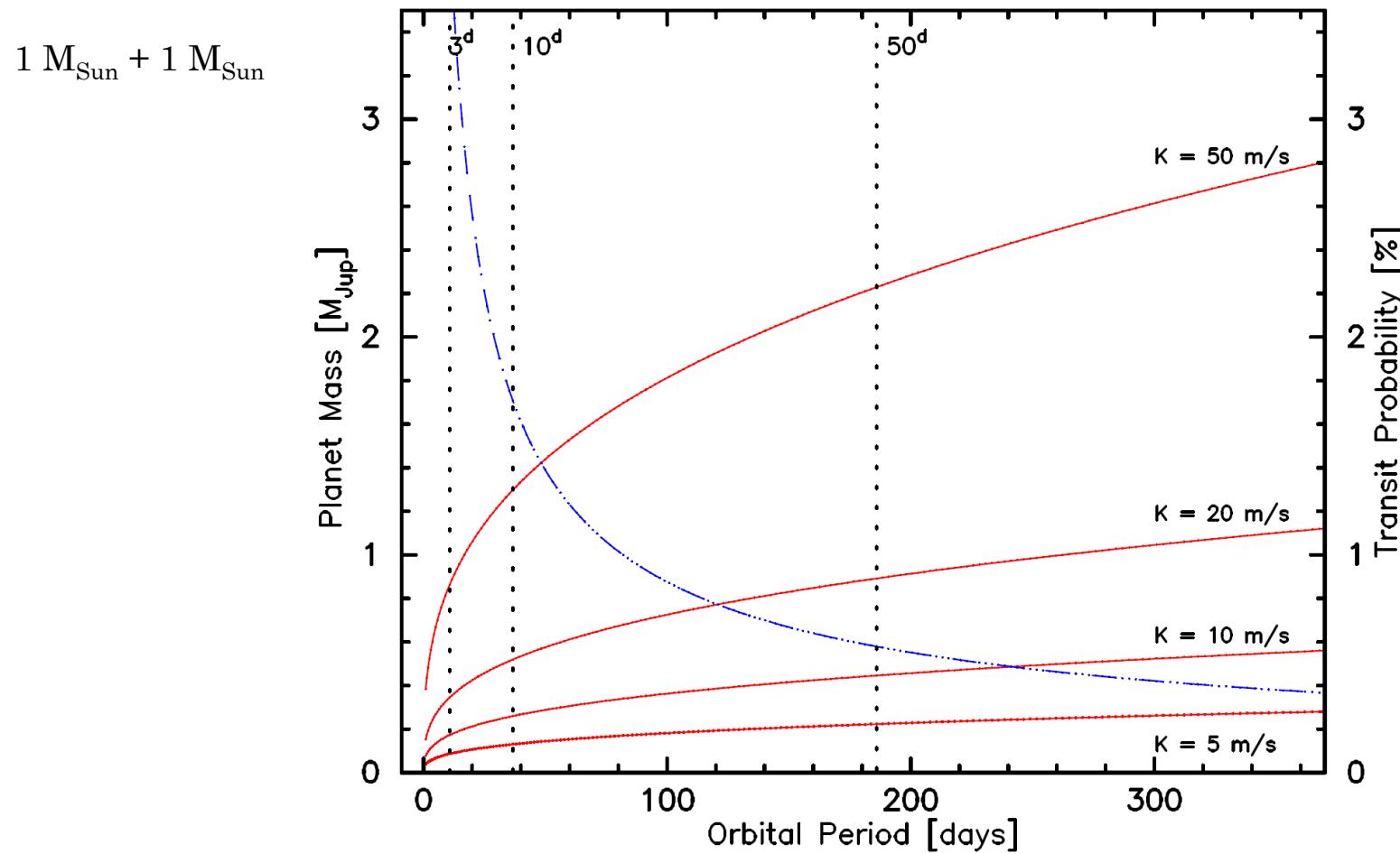


FIRST RESULTS FROM TATOOINE PROJECT – LIMITS TO PLANETS FOR 10 SB2S



Konacki, Muterspaugh, Kulkarni & Helminiak, ApJ, 2009

CIRCUMBINARY TRANSITING PLANETS



Konacki, IAU 253, 2009

PALOMAR TESTBED INTERFEROMETER (PTI)



NS 110 m
NW 86 m
SW 87 m
K (2.2 μ m), H (1.6 μ m)



BINARY STAR RELATIVE ASTROMETRY WITH PTI

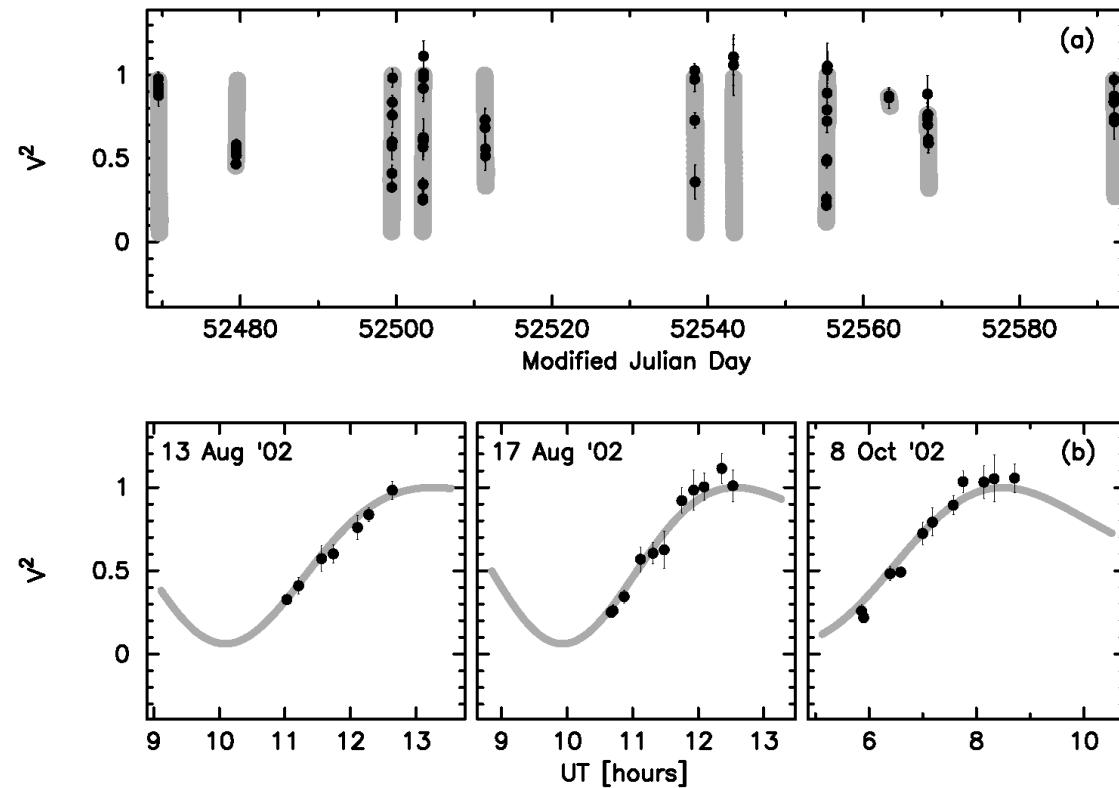
HD 6118

B9.5V+B9.5V

$a = 5.6 \text{ mas}$

$P_{\text{orb}} = 81 \text{ d}$

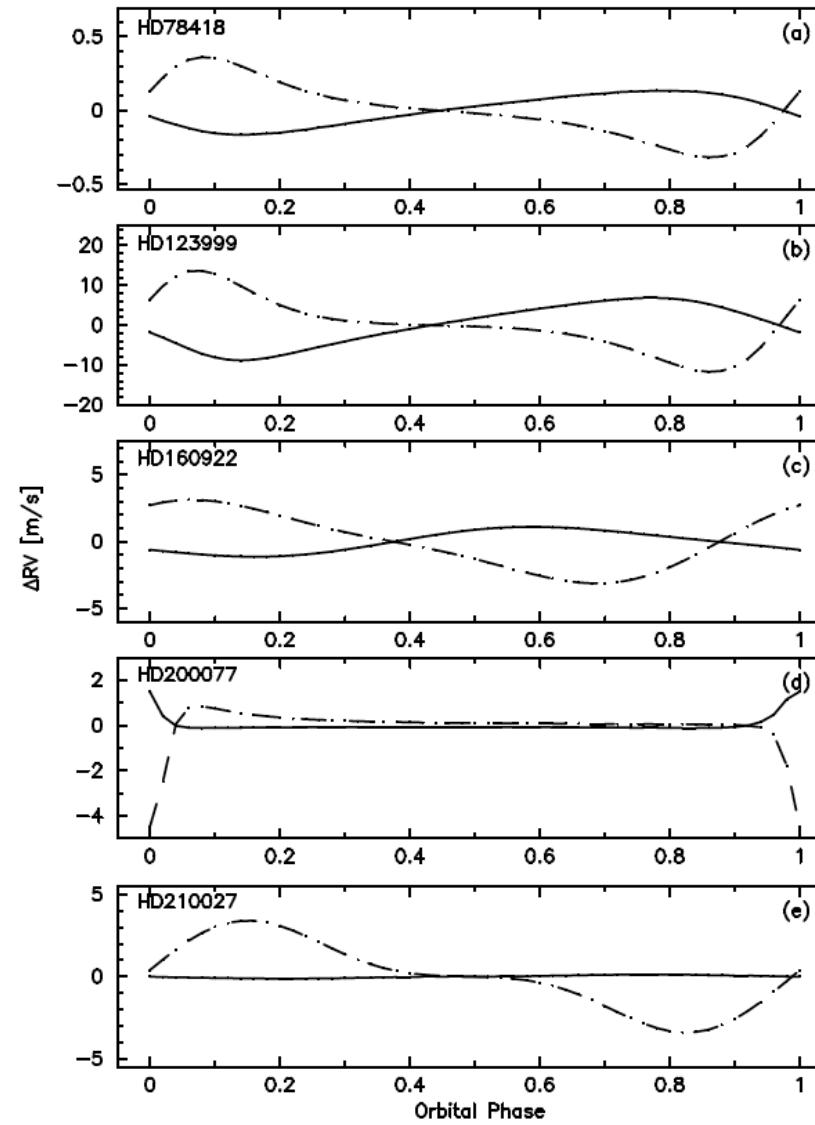
$r = 0.7$



$$V_{\text{binary}}^2 = \frac{V_1^2 + r^2 V_2^2 + 2r V_1 V_2 \cos(2\pi \mathbf{B}_\perp \cdot \Delta \mathbf{s} / \lambda)}{(1+r)^2}$$



TIDAL EFFECTS

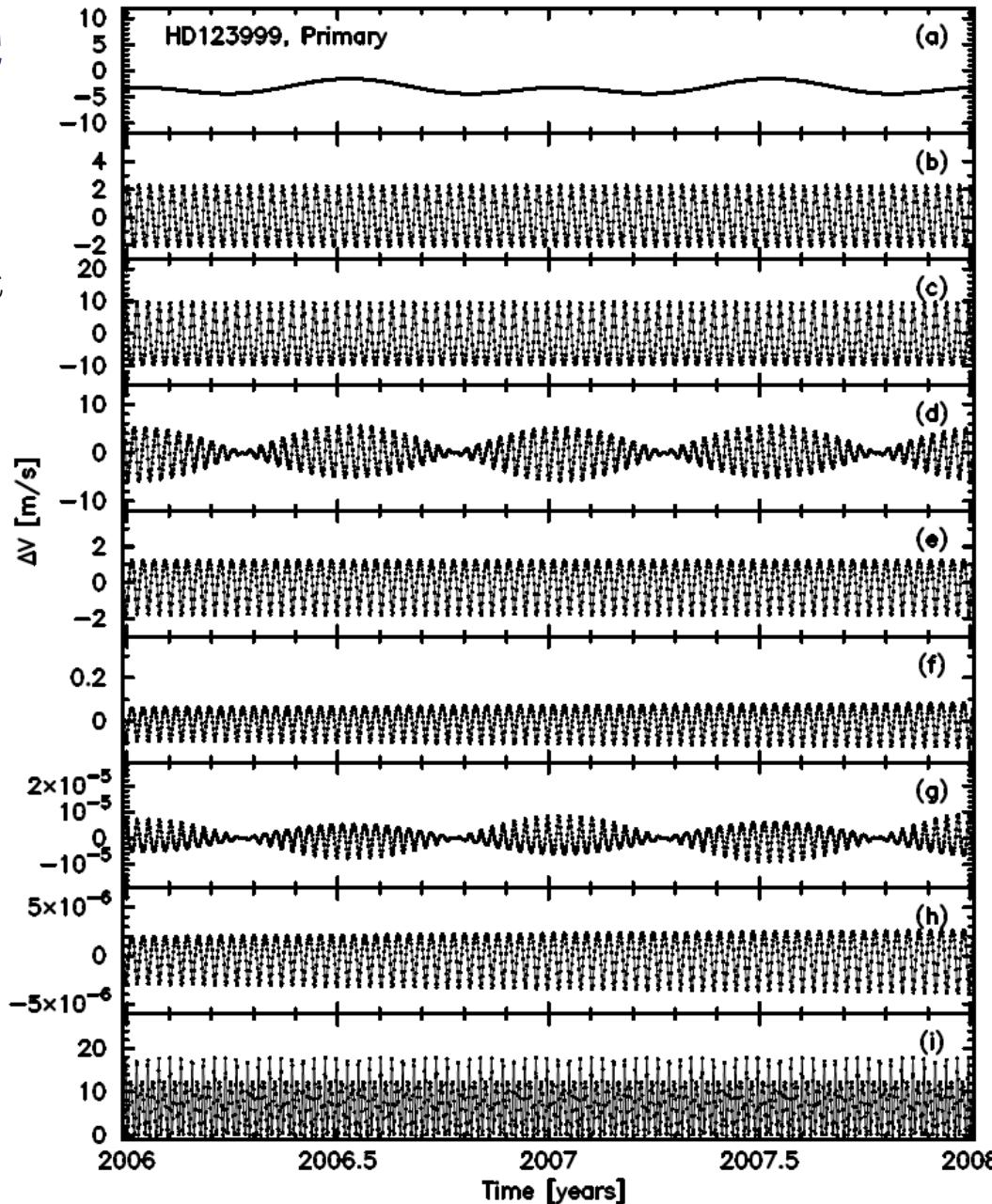


Konacki et al 2010, submitted to ApJ, astroph/0910.4482

RELATIVISTIC EFFECTS

Gravitational redshift
+ transverse Doppler effect

Light time effect



DERIVATION OF ORBITAL INCLINATION FROM JUST RVs OF SB2S, THANKS TO GR

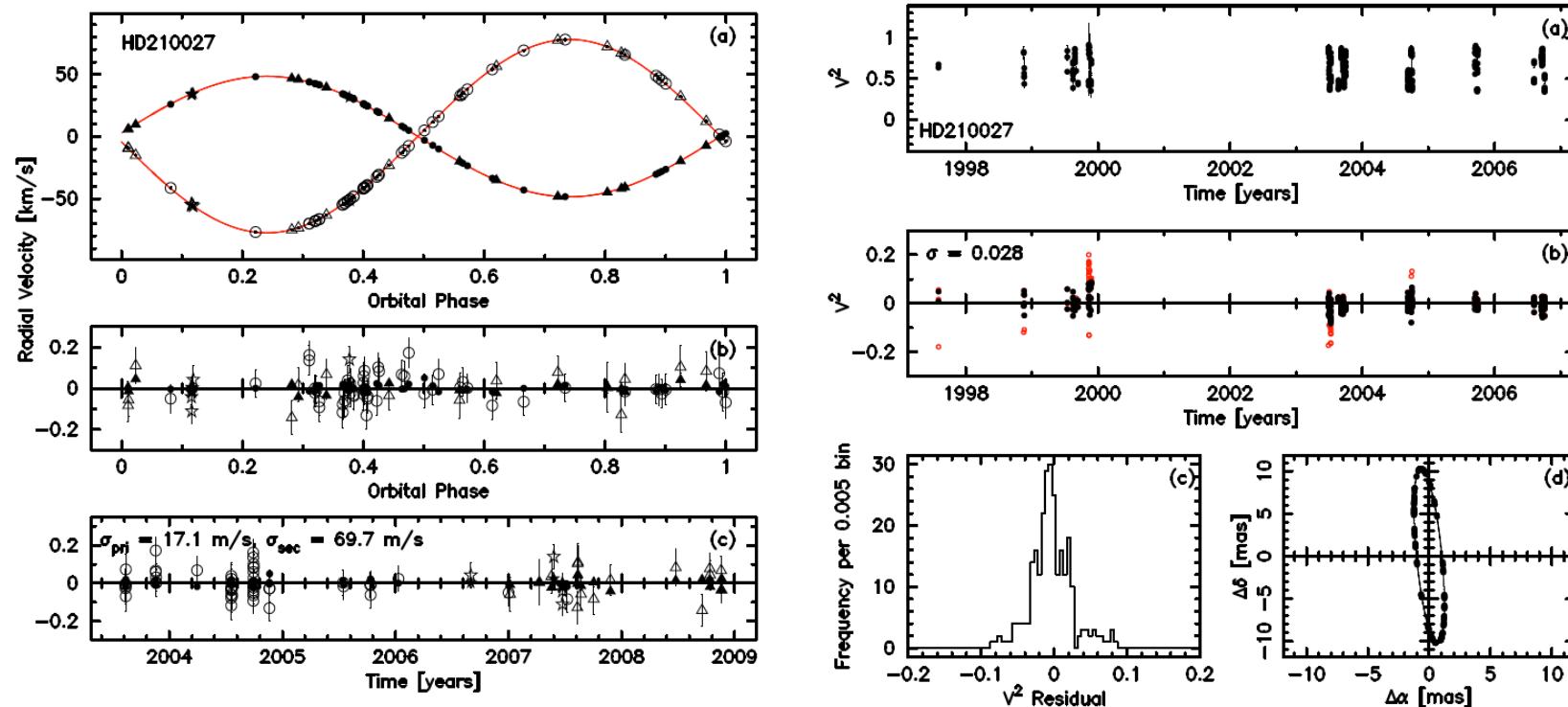
$$\left(\frac{1}{2}\mathcal{V}^2 + U_C\right)_{\text{periodic}} = \gamma_{1,2} \cos f, \quad \gamma_{1,2} = \frac{GM_{2,1}(M_{1,2} + 2M_{2,1})}{ca(M_1 + M_2)} \frac{e}{(1 - e^2)}$$

$$\gamma_{1,2} = \frac{K_{1,2}(2K_{1,2} + K_{2,1})}{c \sin^2 i} e$$



See Zucker & Alexander (2007), and Konacki et al 2010, astroph/0910.4482

RVS+V² PTI ASTROMETRY – AN EXAMPLE, IOTA PEGASI

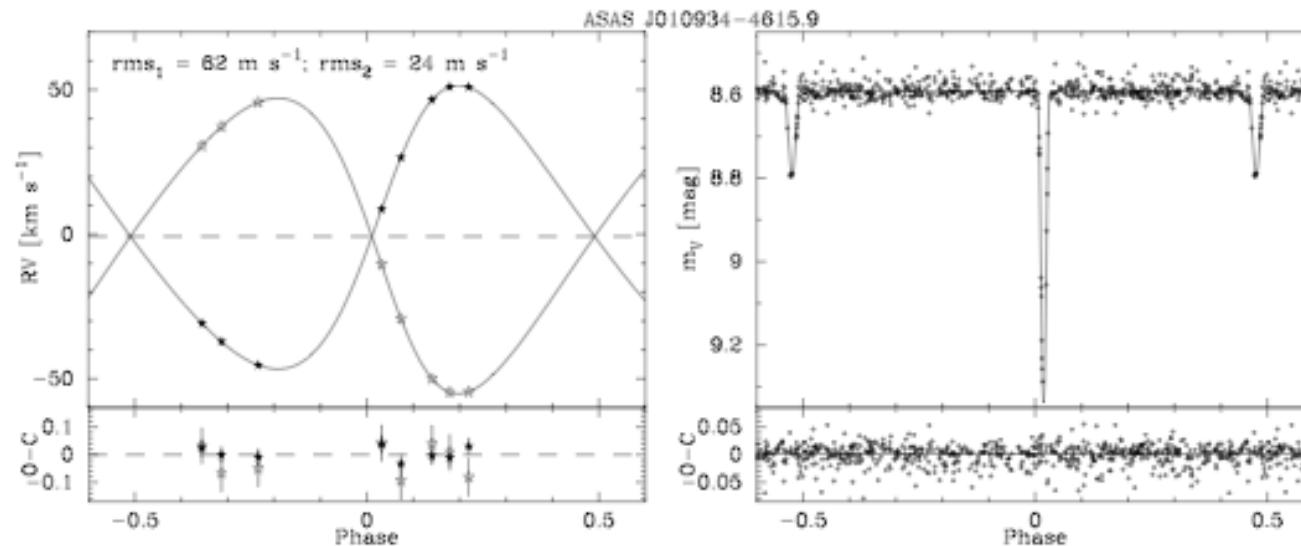


V² by A. Boden, now in PTI archive

$M_1 = 1.33249(89)$, $M_2 = 0.83050(55)$ – The most accurate mass measurement for a pair of normal stars, $\Delta M/M = 0.066\%$



THE (NEAR) FUTURE – OUR RVs + ECLIPSING BINARIES, AN EXAMPLE AI PHE



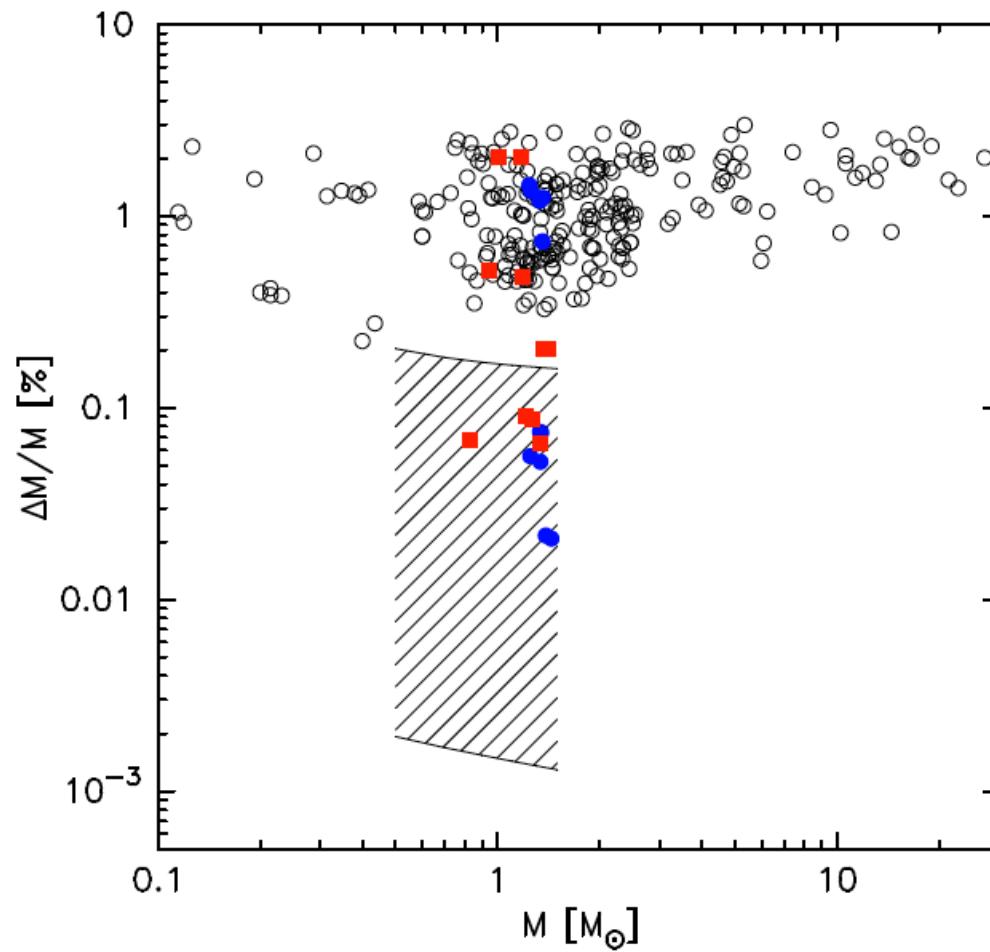
Helminiak, Konacki, Muterspaugh & Ratajczak et al, 2009

With just average RVs (4-m AAT/UCLES+iodine cell, but poor seeing): precision in masses 0.1%. **We can easily do 10 times better.**



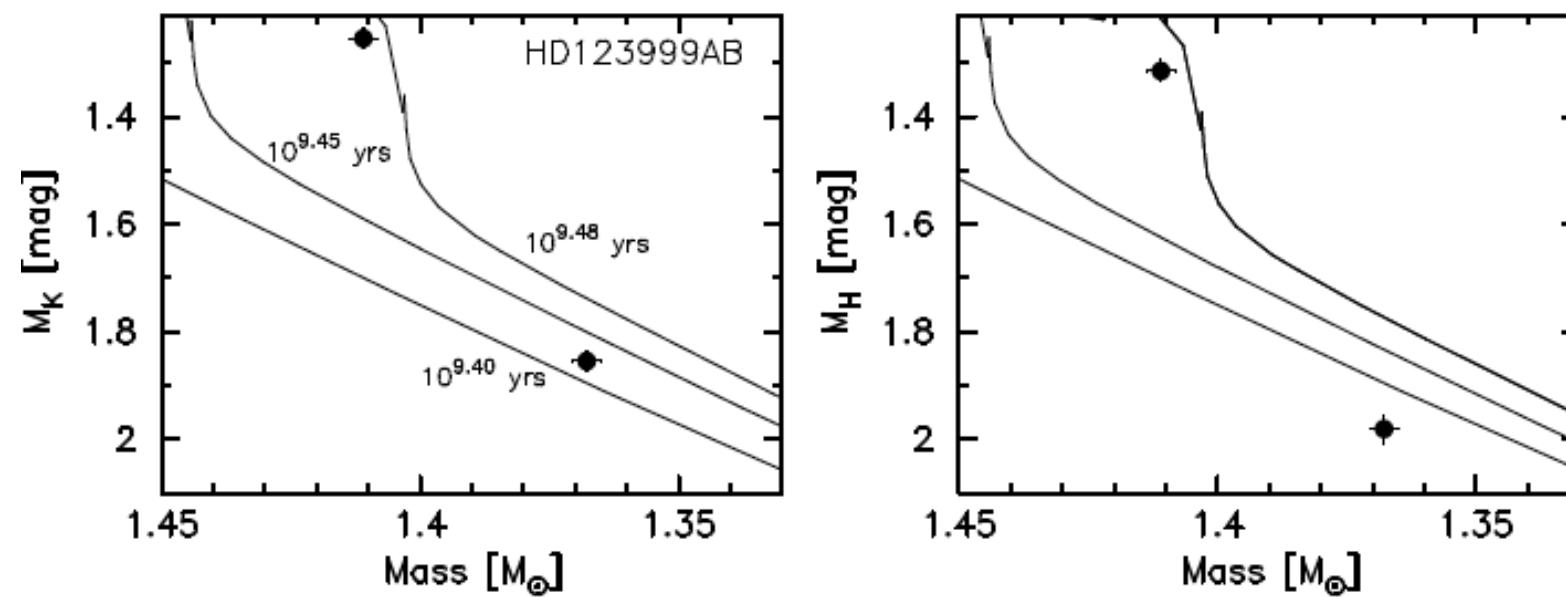
BINARY STARS – PRECISION IN MASSES

Torres et al, 2010



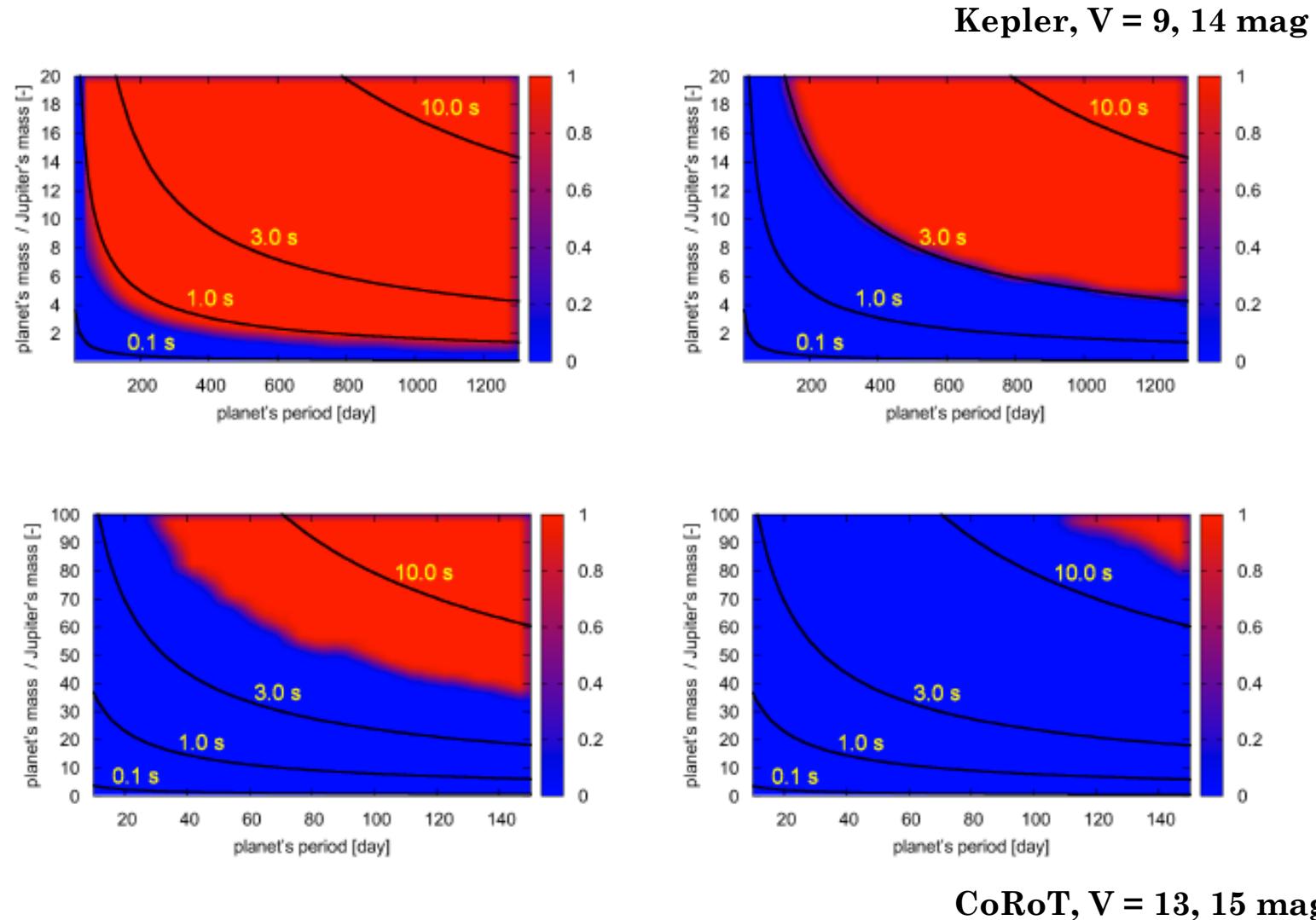
Konacki et al 2010, submitted to ApJ, astroph/0910.4482

TESTS OF STELLAR STRUCTURE AND EVOLUTION MODELS – AN EXAMPLE

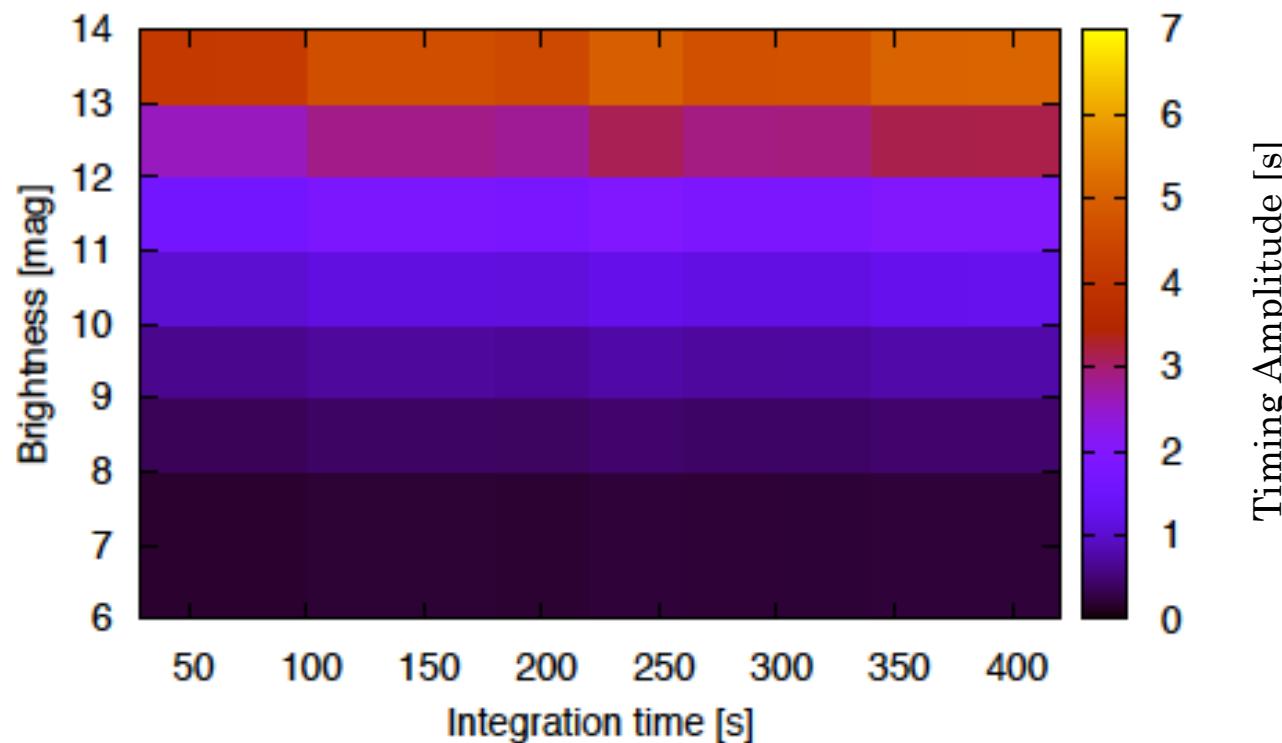


Konacki et al 2010, submitted to ApJ, astroph/0910.4482

CIRCUMBINARY PLANETS, ECLIPSE TIMING WITH KEPLER AND CoRoT



CIRCUMBINARY PLANETS, ECLIPSE TIMING WITH A 0.5-M TELESCOPE



$A = 1 \text{ sec}$, $\sim 2 \text{ Jupiter masses}$ @ $P = 3 \text{ years}$, $M_* = 2 M_{\text{Sun}}$



DETECTION OF CIRCUMBINARY PLANETS WITH DIFFERENT TECHNIQUES

